Purdue University
Purdue e-Pubs

International Refrigeration and Air Conditioning Conference

School of Mechanical Engineering

2012

Experimental Investigations On Falling-Film Absorbers With Horizontal Tubes – A Review

Cord Tomforde
tomforde@uni-kassel.de

Andrea Luke

Experimental Investigations on Falling-Film Absorbers with Horizontal Tubes – a Review

Cord TOMFORDE[1]*, Andrea LUKE[1]

[1]University of Kassel, Institute of Technical Thermodynamics,
Kassel, Germany
+49 (0)561 804 3269, tomforde@uni-kassel.de

* Corresponding Author

ABSTRACT

It is necessary to improve the energy efficiency of all technical processes due to the uncertainties associated with climate change. One possibility to achieve higher energy efficiency is to utilize waste heat which occurs in many different applications. This heat may be used to replace compression chillers by heat driven absorption chillers which leads to a lower consumption of primary energy. Thus, research on heat driven absorption chillers is important to gain higher energy efficiency.

In most cases the absorber is the limiting component of absorption chillers which is often designed as a falling-film absorber with horizontal tubes. This paper gives a brief overview on the latest experimental results of absorption on horizontal tubes published in the literature. All important design parameters and their influence on the efficiency of absorbers are considered. This includes the different working fluids and their additives as well as the various geometrical parameters. Thereby, a special focus is put on the different surface structures of the tubes that are used in absorbers. Also recent trends in research as ionic fluids and nanoparticles are examined. As an important result it can be concluded that some design parameters and their effects on the efficiency of absorbers are still not completely understood. Due to this, possibilities for further investigations are given.

1. INTRODUCTION

In the last decade global warming and its effects on the environment have been of great interest. The global warming is affected by the emission of greenhouse gases (GHG) which have grown over the last decades due to human activities. Although carbon dioxide is the most important greenhouse gas, the influence of common refrigerants used in compression cycles cannot be ignored due to their very high global warming potential, e.g. R134a has a GWP of 1300 (IPCC, 2007). Thus, alternative concepts for cooling are of rising interest. Absorption chillers are such an alternative because of their environmentally friendly working pairs as NH_3 / H_2O and H_2O / LiBr.

Furthermore, the design and operation of energy efficient processes are key engineering tasks in all areas of process industry. Optimization of heat integration may contribute to increased energy efficiency of these processes. Absorption chillers offer the opportunity to increase the efficiency of production processes by supplying the cooling due to the utilization of industrial waste heat. This leads to a lower consumption of primary energy and thereby to reduced emissions of carbon dioxide. Another advantage of this heat integration is the increasing competitiveness.

A very simple absorption cycle consists of four heat exchanger, two valves and one solution pump, where the heat exchanger are the most important and critical components. Unfortunately, the performance and reliability of absorption systems is still not comparable with common compression systems. Hereby, the absorber has been identified as the most critical component of such a system (Beutler *et al.*, 1996). Additionally, Gluesenkamp *et al.*, (2011) pointed out that the design of compact heat exchangers is one of the most important tasks.

The aim of this work is to give an overview on the most important experimental investigations on falling-film absorbers with horizontal tubes published since the review of Killion and Garimella (2003). Geometrical aspects like surface structure, tube diameter and spacing as well as different working fluids and their additives are covered in this paper. Some information are summarized in an analogue way to Killion and Garimella (2003) allowing a better comparison of all studies discussed in both reviews. Possible strategies for more efficient absorber designs are pointed out and tasks for further experimental investigations are named in this review.

2. TYPICAL DESIGN OF EXPERIMENTAL SETUPS AND OPERATING CONDITIONS

Most of the investigations discussed in this review are performed at an absorber test stand. Although all test setups have their own specific details, the general design of these test stands is comparable. A typical design of this type of test setup is shown in Figure 1. In such an experimental setup, the absorber and the generator are located in one casing and they are at the same pressure level. The vapor is often generated directly beneath the absorber bundle by an electrical heater and vapor flows in counter-current flow to the solution. The poor solution is pumped from the bottom to the top of the absorber and the solution temperature is in many cases conditioned on this way. Different approaches of solution distribution are used to get a full wetting of the first tube row. The solution absorbs the vaporous refrigerant while it flows down the tube bundle, increasing the concentration of the refrigerant within the solution. In many cases, the enriched solution is collected in a tub beneath the last tube row in order to measure its conditions. The coolant flows typically in a serpentine way from the bottom to the top of the absorber. A variety of different data is measured in such a test stand. At least, the overall temperature change and the flow rate of absorbent and coolant as well as the system pressure, the heating power and the concentration of the poor solution are determined. In some cases, additional temperature measurements are conducted at various points of the absorber and the concentration of the strong solution beneath the absorber bundle is measured. Especially, the measurement of the concentration is quite complicated due to the low concentration differences between poor and rich solution. Therefore, no standard approach for this measurement is available in literature. A more detailed description of this typical design is given by Killion and Garimella (2003).

In a few investigations, a complete single-effect absorption chiller is used for the experiments (Yoon *et al.,* 2002, Bredow *et al.*, 2008, and Kyung and Herold, 2002). The advantage of this attempt is that the obtained data are more realistic in comparison with available commercial systems. Unfortunately, they are limited in the determination of basic mechanisms leading to heat and mass transfer enhancement due to the interactions between the different components. Kim *et al.*, (2003a) focused on the wettability of the tube bundle in absence of heat and mass transfer and Pospisil *et al.*, (2009) investigated only the heat transfer enhancement and backsplash in dependence of the surface structure. Therefore their experimental setups differ slightly from the typical design described above. Information on these test setups is given as the investigations are discussed.

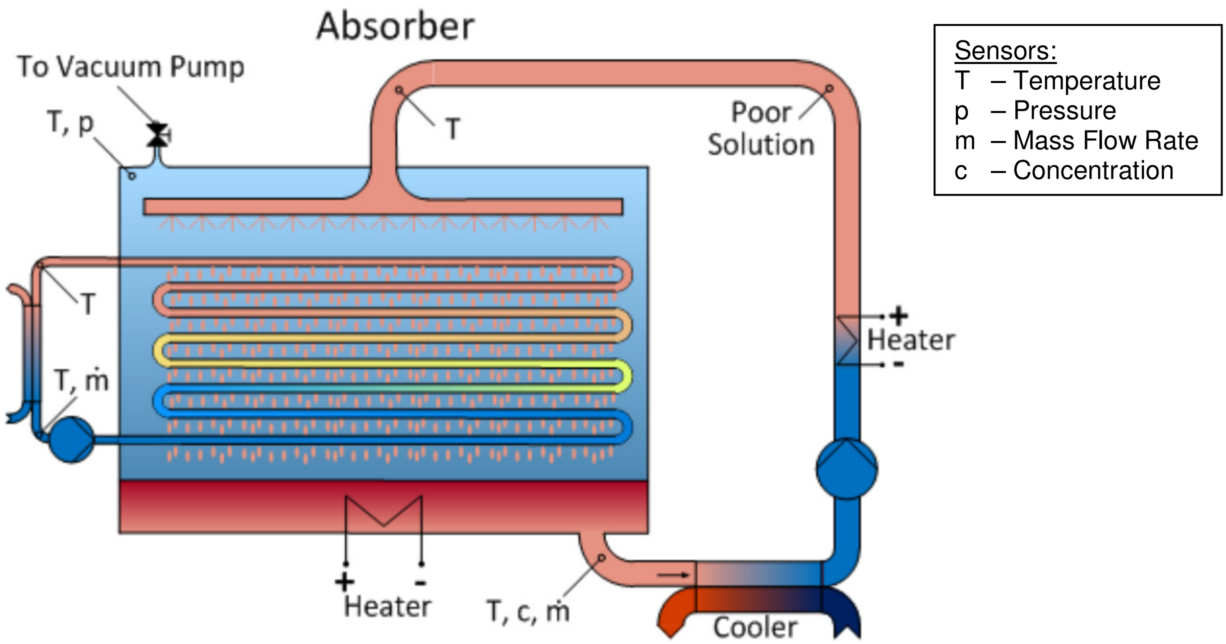


Figure 1: Typical Design of a Test Apparatus for Falling-Film Absorbers with Horizontal Tubes

Table 1: Summary of the Absorber Designs and Working Fluids used in the Reviewed Investigations

Author(s)	Working Fluid	Additive	Number of Tubes	Tube OD [mm]	Tube Length [mm]	Center-Center / Diameter	Surface Structure	Coolant flow
Kyung & Herold (2002)	H_2O / LiBr	2-Ethyl-Hexanol	4 / 8	19.1	360 / 460	2,33	smooth	serpentine
Nosoko *et al.* (2002)	H_2O / O_2	-	2 / 4 / 6 / 8	16.0	284	1,125 – 1.94	smooth	-
Yoon *et al.* (2002)	H_2O / LiBr	n-Octanol	8	15.9	400	1.5	smooth / 2 enhanced	parallel flow
Kim *et al.* (2003a)	H_2O / LiBr	-	28	16.0	205	1.625	smooth / 2 enhanced	-
Kim & Lee (2003)	H_2O / LiBr	-	6	22.0	100	-	smooth	serpentine
Park *et al.* (2003)	H_2O / LiBr	-	24	16.0	500	1,7	smooth / 2 enhanced	serpentine
Frances & Ojer (2003)	H_2O / LiBr	-	14	15.9	330	2.95	smooth	serpentine
Kyung *et al.* (2007)	H_2O / LiBr	-	4 / 8	19.0	360 / 470	2,33	smooth	serpentine
Kang *et al.* (2008)	H_2O / LiBr	nano-particles	8	15.0	500	3,5	smooth	serpentine
Yoon *et al.* (2008)	H_2O / LiBr	-	10 / 12 / 16	15.9 / 12.7 / 9.5	400	1,63	smooth	serpentine
Islam (2008)	H_2O / LiBr	-	24	19.0	160	-	smooth	serpentine
Pospisil *et al.* (2009)	H_2O	-	10 / 20	12.0	1000	1.25…2.5	smooth / 4 enhanced	serpentine
Harikrishnan *et al.* (2009)	R134a / DMAC	-	48	12.7	1000	-	smooth	serpentine

The range of the working fluids, additives and different geometrical parameters used in the experimental investigations of the last years is summarized in chronological order in Table 1. It has to be noted that only the first description of an experimental setup in literature is listed in this table, but often an identical setup is used for a series of investigations. Detailed information on other parameters, e.g. mass flow rate, is given in the following discussion of the different investigations. Obviously, there are some parameters which are almost identical within all investigations. Most studies discussed (in this review) apply a H2O/LiBr solution as working fluid, tube diameters from 15.9 to 19 mm and a serpentine way of coolant flow within the tubes. A wide scattering of the experimental conditions is observed for the number of tubes, tube length and the ratio of tube distance divided by tube diameter. Due to the chronological order of the listed test setups, a trend to smaller tube diameters can be seen for the last few years. Other specific trends cannot be identified in the listed experimental conditions.

3. EFFECT OF WORKING FLUIDS AND ADDITIVES

Some investigations on new possible working fluids for absorption chillers are conducted in the last decade. This is of high interest because of the very limited number of available working fluids so far. In this work, experimental results on the employment of so-called ionic liquids and a R134a-DMAC mixture in falling-film absorbers are reported. Additionally, there are many different investigations on the effect of different additives on heat and mass transfer in absorption chillers. Research on well-known additives as n-Octanol as well as on nanoparticles is covered in this review.

3.1 Working Fluids

In the last decade several papers have been published containing experimental studies on falling-film absorbers with H_2O/LiBr as working fluid, but no additives are employed and no geometrical parameters are investigated. Most of them (Kyung *et al*., 2007, Soto Francés and Pinazo Ojer, 2003, Raisul Islam *et al.*, 2003, and Raisul Islam, 2008) are performed to validate a model for the absorption of vapor into an aqueous lithium bromide solution. Bredow *et al.* (2008) investigated the influence of the LiBr concentration and solution flow rate on the heat and mass transfer in an industrial type absorption chiller. These experimental investigations are not discussed in detail because the obtained results do not contribute to the topics primarily discussed in this review. Nevertheless, these papers should be mentioned in this review.

Harikrishnan *et al.* (2009, 2011) have investigated the absorption of vaporous R134a (1,1,1,2-tetrafluorethane) into a R134a-DMAC (Dimethylacetamide) solution flowing over a falling-film tube bundle. This tubular absorber consists of 48 copper tubes which are arranged in 6 columns with 8 rows. The diameter of each tube is 12.7 mm and the effective length is 1000 mm. In 2009, the effects of solution subcooling and solution flow rate on heat and mass transfer are investigated. The obtained results are compared with typical values when a lithium bromide solution is used in such a system. The reported heat transfer coefficients are in the range from 100 – 400 W/m²K, which is only about a tenth of the values for H_2O/LiBr. The heat transfer coefficient seems to be only dependent of the solution flow rate. The values obtained for the mass transfer coefficient are strongly dependent on the solution subcooling. The range observed for low subcooling is from 200 to 300 g/m²s. A mass transfer coefficient of about 20 g/m²s is reported for high subcooling. In comparison with H_2O/LiBr, the mass transfer coefficients are of the same order. Harikrishnan *et al.* (2011) have extended their investigations on this working fluid. They have varied mass flow rate of the coolant, coolant temperature, heater load and concentration of R134a in the solution in this experimental study. Unfortunately, it is not pointed out which of these parameters has the strongest effect on heat and mass transfer and for the obtained results no comparison with a typical working fluid as H_2O/LiBr is provided.

Schneider et al. (2011) investigate the use of ionic liquids as possible new working fluids for absorption chillers. They point out that the ionic liquids can be customized onto the requirements of a specific process. Thus, the well-known drawbacks of the common working pairs H_2O/LiBr and NH_3/H_2O as corrosiveness, crystallization, toxicity or working pressure can maybe solved with these new substances. The experimental investigations are performed at a single-effect absorption chiller. All heat exchanger are realized as horizontally orientated tube bundles, but no detailed geometric information is provided. Three different ionic liquids are compared with the typical working fluid H_2O/LiBr. It is shown that comparable or even better COPs can be obtained with ionic liquids, but the higher viscosity of all ionic liquids leads to a far lower solution flow rate. This results in a lower cooling capacity for all tested ionic liquids compared with H_2O/LiBr.

3.2 The Effect of Additives

The additives used in horizontal tube absorbers can be categorized in two independent groups. These are already well-known surfactants as 2-Ethyl-Hexanol or n-Octanol and nanoparticles as Fe particles or carbon nanotubes (CNT) which are a new trend in absorption research. Both types lead to a dramatic increase in absorber efficiency, but at least for the nanoparticles the effect cannot be explained in a sufficient way.

The effect of surfactants on heat and mass transfer in absorption chillers is studied by Yoon *et al.* (2002), Park *et al.* (2004) and Kyung and Herold (2002). The effect of n-Octanol (Yoon *et al.,* 2002, Park *et al.,* 2004) and 2-Ethyl-Hexanol (Kyung and Herold 2002) is analyzed in these investigations. Yoon *et al.* (2002) use in their investigation a full absorption cycle and the absorber consists of 48 tubes of 400 mm length. The tubes are arranged in 6 columns and 8 rows and the experiments are conducted without and with an additive. Octanol is used as additive and the concentration is varied from 500-5500 ppm. 3 different tube surfaces are used in this investigation. They present only results for the effect of surfactant concentration on the heat transfer coefficient. No information on the mass transfer coefficient is given in the paper. An enhancement up to 90% is observed for the smooth tube in dependence of the surfactant concentration, but no further improvement of the heat transfer is obtained for additive concentrations higher than 3500 ppm. The effect of the enhanced surfaces is discussed in the next section.

Park *et al.* (2004) investigate the influence of the same surfactant on the heat and mass transfer in a falling-film absorber consisting of 24 tubes. They use 3 different surfaces in their investigation, one smooth tube and two enhanced ones. The tubes have a diameter of 16.0 mm and the length is given with 500 mm. The concentration of n-Octanol is given with 400 ppm. For the smooth tube, Park *et al.* (2004) report an enhancement of 3.76 times in presence of the surfactant compared with the absorption rate without additive.

Kyung and Herold (2002) investigate the performance of horizontal smooth tube absorbers with and without 2-Ethyl-Hexanol in a single-effect absorption chiller. The tubes have an outer diameter of 19.1 mm and two tube bundles are tested in this investigation. One consists of eight tubes with a length of 460 mm and the other one consists of 4 tubes of 360 mm length. The distance between the tubes is 25.4 mm in both configurations. The concentration of the additive is varied from 0 to 500 ppm and it is found that a maximum enhancement is reached at a concentration of 100 ppm. A heat transfer enhancement of 1.67 times compared with the value without additive is reported. This enhancement is explained with the Vapor Surfactant theory which was introduced by Kulankara and Herold (1999).

Most investigations on the effect of nanoparticles on the coupled heat and mass transfer have been performed with other absorber geometries as falling-film absorber with horizontal tubes. Only Kang *et al.* (2008) investigated the effect of nanoparticles on the heat and mass transfer in such an absorber. Their test absorber consists of 8 parallel tubes with an outer diameter of 15 mm and an effective length of 500 mm. H2O/LiBr is used as working fluid in the experiments and Fe particles and carbon nanotubes are added in concentrations of 0.01 and 0.1 wt% to the solution. They observe a significant enhancement of the vapor absorption rate with increasing concentration of both kinds of nanoparticles but the influence of the nanoparticles on the heat transfer rate seems to be almost negligible. Kang *et al.* report that the CNT lead to a higher mass transfer enhancement than the Fe nanoparticles and an average enhancement factor of 2.48 is given for a concentration of 0.1 wt% CNTs. Therefore, they conclude that CNT are more suitable for H_2O/LiBr absorption systems than Fe nanoparticle.

A significant enhancement of the absorber efficiency can be achieved when additives are used in such a system. Because of the limited number of investigations on the influence of nanoparticles it is not possible to decide which kind of additive is more efficient. The mechanisms of the enhancement by adding surfactants has already been investigated in the last decades (Killion and Garimella 2003), but a sufficient explanation of the mechanism of mass transfer enhancement by adding nanoparticles is missing and further research is necessary. Furthermore, the combined usage of both additive types is of high interest and the impact on each other should be addressed in this context.

4. EFFECT OF GEOMETRICAL PARAMETERS

The design of falling-film absorbers with horizontal tubes contains several independent geometrical parameters as the surface structure of the tubes, tube diameter, tube spacing and the number of tubes per column. Other parameters like the solution distribution, vapor inlet into the absorber and solution collection will not be discussed within this review because they are not directly related to the geometrical design of the horizontal tube bundle.

4.1 Micro- and Macrostructure of the Tubes

Modifications of the tube surface can be separated into micro- and macro-structured surfaces. Both types of modification have been discussed in literature during the last decade and their influence on surface wetting of a horizontal tube bundle as well as heat and mass transfer has been investigated. Two different sanded and one sand-dressed (sandblasted) surface have been used as micro-structured surfaces and one ribbed, one single- and one double-grooved tube have been investigated. Additionally, one tube with a hydrophilic surface coating is used by Yoon *et al.* (2002). All discussed surface modifications are summarized in Figure 2.

The influence of two helically sanded surfaces on heat and mass transfer and surface wetting has been investigated in a series of studies by Kim *et al.* (2003a, 2003b), Park *et al.* (2003, 2004) and Kang and Kim (2006). In all investigations the results of these two tubes are compared with a smooth tube. The surface roughness of the helically grooved tubes is given with 0.384 μm and 6.986 μm, respectively. Unfortunately, there is no detailed analysis of the surface structure and the roughness given in the papers. In both cases, the helix has an angle of 60°. Kim *et al.* (2003a) focus on the effect of surface modification on the wettability of a horizontal tube bundle. They use an arrangement of 28 copper tubes in one column. All tubes have a length of 205 mm and the mass flow rate of the H_2O/LiBr solution is varied from 0.74 to 2.71 kg/min. They show that a higher wettability is achieved with increasing surface roughness and empirical correlations for the wettability of the tube bundle are proposed for smooth and enhanced surfaces. In a numerical study Kim *et al.* (2003b) investigated the influence of the surface modifications on heat and mass transfer. Their numerical analysis showed that there is a significant improvement in performance due to surface treatment, which is explained with the enhancement of the wettability.

Park *et al.* (2003, 2004) investigated the influence of micro-scale surface treatment on heat and mass transfer in an absorber. Their absorber consists of 24 tubes in a single column and each tube has a length of 500 mm. A H_2O/LiBr solution is used as working fluid. The experiments are conducted with and without the use of an additive (n-Octanol, 400 ppm). Ethylene glycol is used as coolant and flows in a serpentine arrangement from the bottom to the top of the test section. In the absence of additives they observed a significant increase in absorption rate for both enhanced surfaces compared with the smooth tube. This is explained with the higher wettability of the sanded tubes and it is pointed out that the effect becomes more significant with increasing solution flow rates. The maximum absorption performance of both enhanced surfaces is about two times of that of the smooth tubes. The effect of the mechanical surface treatment becomes less important in the presence of 400 ppm n-Octanol. Nevertheless, for the tube with a surface roughness of 6.986 μm an enhancement of about 20% is still observed compared with the smooth surface in the presence of an additive. Kang and Kim (2006) presented identical results.

Yoon *et al.* (2002) and Pospisil *et al.* (2009) reported results on the effect of macro-structured surfaces on the rate of heat transfer in falling-film absorber. Yoon *et al.* (2002) compare the heat transfer on a horizontal tube bundle for ones consisting of smooth tubes, hydrophilic tubes and floral tubes. All tubes have the same outer diameter of 15.88 mm. The experimental setup is described in the former section. In absence of additives, the hydrophilic tube shows the best performance with a heat transfer coefficient 10-35% higher depending on the flow rate than the smooth tube. The floral tube has the highest heat transfer coefficient when n-Octanol is added to the system, but it must be mentioned that the additive has a higher influence on the rate of heat transfer than the use of structured tubes.

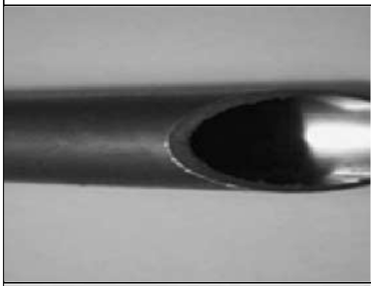
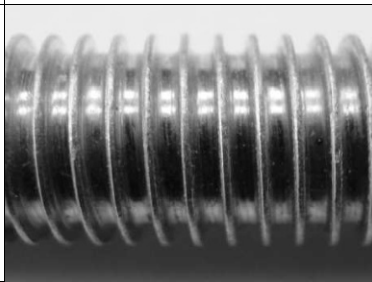
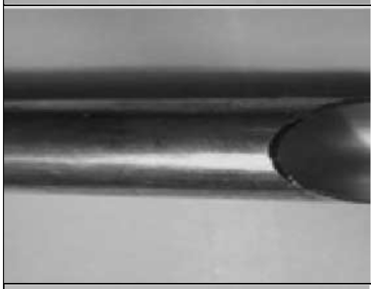
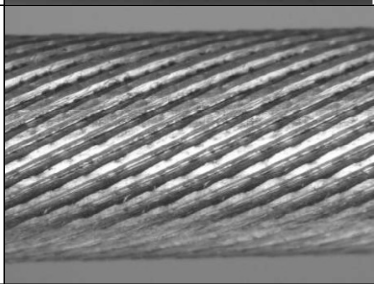
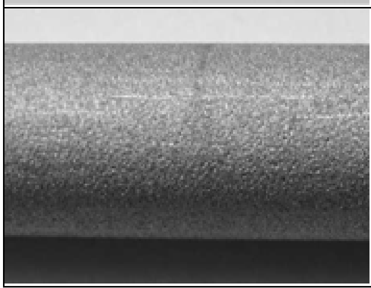
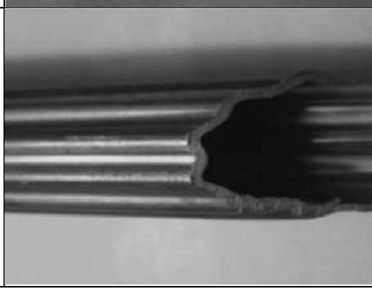
Micro-structured Tubes		**Macro-structured Tubes**	
	smooth tube; OD = 15.88 mm; Yoon *et al.* (2002)		finned tube; OD = 12 mm; Pospisil *et al.* (2009)
	hydrophilic tube; OD = 15.88 mm; Yoon *et al.* (2002)		single-grooved tube; OD = 12 mm; Pospisil *et al.* (2009)
	helically sanded tubes; OD = 16 mm; ε = 0.384 μm / 6.986 μm; Kim *et al.* (2003a, 2003b), Park *et al.* (2003, 2004)		double-grooved tube; OD = 12 mm; Pospisil *et al.* (2009)
	sand-dressed (sandblasted) tube; OD = 12 mm; Pospisil *et al.* (2009)		floral tube; OD = 15.88 mm; Yoon *et al.* (2002)

Figure 2: Different surface structure of tubes used in falling film absorbers

Pospisil *et al.* (2009) studied the influence of surface modification on the heat transfer coefficient for different flow rates and tube spacings. They use a falling film tube bundle consisting of ten copper tubes with a length of 1000 mm. A smooth tube, a sand-dressed tube, two different finned tubes, a single grooved tube and a double grooved tube are used in the experiments and the tube spacing is varied from 15 to 35 mm. Water is the working fluid. Unfortunately, the different enhanced tube surfaces are not described in detail. They report increasing heat transfer coefficients with increasing flow rates but due to a high scattering of their results it is not possible to identify the influence of the different surface structures on the heat transfer coefficients.

All above mentioned results are in agreement with those reported by Killion and Garimella (2003). There has not been a systematic investigation on the interaction between additives and surface modification on the efficiency of absorbers, although it is known that these two parameters directly affect each other. Furthermore, in some cases only the effect of surface modifications on heat transfer coefficients are reported, but the change in mass transfer is not directly proportional to heat transfer. This is especially the case in presence of additives as shown by Miller (1999). Therefore, further research on the influence of surface modifications, especially in presence of additives, is recommended to identify quantitative correlations for heat and mass transfer.

4.2 Tube Diameter and Spacing

Although tube diameter has an important effect on heat and mass transfer in falling-film absorber, there are only very few investigations directly related to this parameter. As listed in Table 1 most tube diameters used in the investigations during the last decade are in a range from 15.9 to 19.0 mm outer diameter. This is nearly identical with the range reported by Killion and Garimella (2003). The influence of tube diameter on absorber efficiency has been investigated by Yoon *et al.* (2008). They compared influence on heat and mass transfer of three tubes with an outer diameter of 15.88, 12.70 and 9.52 mm, respectively. The different tubes all were mounted in one absorber consisting of three columns. In each column the pitch to diameter ratio is 1.63. The flow path of the strong solution is controlled with three valves, one at the top of each column. Compared with the tube diameter of 15.88 mm, the heat and mass transfer coefficients reported by Yoon *et al.* (2008) are 9.8 and 11.8 % higher for the smallest tube diameter of 9.52 mm. This result is shown in Figure 3.

This is in good agreement with the results obtained by Jeong and Garimella (2005), who showed in a numerical investigation that smaller tube diameters lead to an enormous increase of cooling capacity for absorbers with the same heat transfer area. They compared tubes with a diameter of 15.88, 6.35 and 3.175 mm. The ones with the smallest diameter deliver an increase in cooling capacity of about 55 % when complete wetting of the surface is assumed. This is explained by the increase of absorption during the droplet formation, which is proportional to the number of tubes of the absorber. Although small diameter tubes seem to be advantageous compared with conventional tubes, Jeong and Garimella (2005) point out that a decrease in wetting is expected for smaller tube diameters.

Since there has not been suggested a new correlation on the influence of the tube diameter on the heat and mass transfer, the relationship

$$Nu_f = 0.30 \cdot Re_f^{0.46} \cdot \left(\frac{D}{D_0} \right)^{-0.2} \tag{1}$$

given by Cosienza and Vliet (1990) is still valid, although it is based on a limited number of data. The film Reynolds number is defined as $Re_f = 4\Gamma/\mu$ and $D_0 = 19.5$ mm. Because of the limited knowledge about the influence of tube spacing on heat and mass transfer, additional experimental investigations are suggested. In this context, the relation of the tube diameter and surface wetting should also be examined in order to identify the practical optimum for absorber design.

The effect of tube spacing and the number of tubes has not found much attention in the last decade. Only Nosoko *et al.* (2002) and Pospisil *et al.* (2009) have investigated these parameters for falling-film absorbers with horizontal tube bundles. Unfortunately, both of them did not use one of the typical working fluids for absorption chillers, but the general results might be useful for design considerations of tubular absorbers. Nosoko *et al.* (2002) studied the

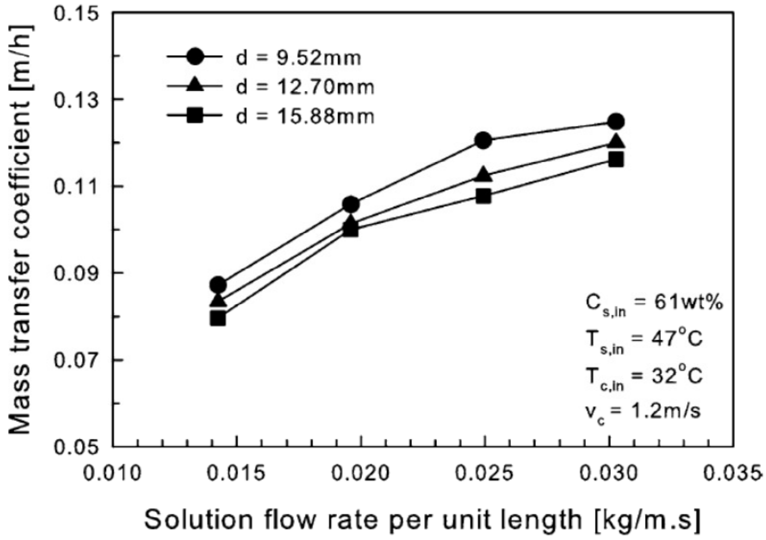


Figure 3: Effect of the diameter and solution flow rate on the mass transfer coefficient (Yoon *et al.*, 2008)

absorption of oxygen into a falling film of water. The absorber consisted of copper tubes with an outer diameter of 16mm in a single-column. The number of tubes has varied from 2 to 8 tubes and the spacing between the tubes was 2, 5, 10 and 15 mm, respectively. The wetted length of the tubes is 284 mm and the experiments are conducted at atmospheric pressure. They report an increase in mass transfer for all investigated film flow rates with an increasing distance between the tubes. This enhancement is explained by the change from a sheetwise film flow to a discontinuous droplet flow for increasing tube distances, which leads to a better mixing of the film on the tube. This result agrees with those of Atchley *et al.* (1998) and Miller (1999) without any surfactant. Unfortunately, the results of Atchley *et al.* (1998) and Miller (1999) do not show such a clear trend, when the experiments are performed with an additive. According to Nosoko *et al.* (2002) the influence of the number of tubes in one column is not as strong as the influence of tube spacing.

Pospisil *et al.* (2009) have investigated the influence of tube spacing on the rate of heat transfer on a falling-film tube bundle. The outer diameter of the copper tubes is 12mm and the center-to-center distance between the tubes is 15, 20, 25, and 35 mm, respectively. Water is used as working fluid in the experiments. Their results show that an increase of film flow rate leads in general to higher heat transfer rates. The highest heat transfer coefficients are obtained with the smallest tube distance, when smooth tubes are used. For the structured surfaces used in their investigation, the results seem to be arbitrary and should be checked in further investigations.

Both, Pospisil *et al.* (2009) and Nosoko *et al.* (2002), showed that the backsplash of the falling film becomes higher with increasing tube spacing and number of tubes. Hereby, it is not completely understood which is the dominant parameter. According to Nosoko *et al.* (2002) the backsplash is negligible for tube distances smaller than 5 mm, but it increases exponentially with flow rate for larger tube distances. Especially for a tube distance of 35 mm, Pospisil *et al.* (2009) reported backsplash rates of more than 70 % of the total flow rate for all investigated flow rates.

Because of the limited knowledge on the effect of the number of tube and spacing between them, further experimental research on these parameters is suggested. Thereby, the influence of backsplash rates on heat and mass transfer in tubular absorbers should be considered.

5. CONCLUSIONS

In this review the latest experimental investigations on heat and mass transfer in falling-film absorbers with horizontal tubes are summarized. Although many different aspects as geometrical parameters of the absorber, different working fluids and their additives are covered in literature, there are still many basic questions to be answered.

Very promising first attempts are presented to develop new working pairs and additives for absorption chillers. Especially the so-called ionic liquids are of great interest because they can be customized onto the requirements of the absorption process. Furthermore, it is shown that the mass transfer coefficient can be enhanced by adding nanoparticles, which are a new class of additives. Unfortunately, the basic mechanism leading to this enhancement is unknown. In both cases, the current state-of-the-art is very low and a substantial amount of research has to be done before these new attempts can be evaluated.

It is shown that the efficiency of tubular absorbers can be enhanced with different geometrical parameters as tube diameter, tube distance or tube surface. Smaller tube diameter, some enhanced surfaces and an increasing tube distance lead to enhanced heat and mass transfer. Unfortunately, the basic mechanisms for the enhancement are not completely understood for all geometrical parameters. More systematic and detailed observations are necessary to achieve progress in this area.

NOMENCLATURE

D	diameter	(m)
Nu	Nusselt number	(-)
p	pressure	(Pa)
Re	Reynolds number	(-)
T	Temperature	(°C)
ε	surface roughness	(µm)
Γ	specific film flow rate	(kg / m s)
µ	dynamic viscosity	(kg / m s)

Subscripts

f	film
0	reference

REFERENCES

Atchley, J.A., Perez-Blanco, H., Kirby, M.J., Miller, W.A., 1998, An Experimental and Analytical Study of Advanced Surfaces for Absorption Chiller Absorbers, *Gas Research Report GRI*

Beutler, A., Hoffmann, L., Ziegler, F., Alefeld, G., Gommed, K., Grossmann, G., Shavit, A., 1996, Experimental Investigation of Heat and Mass Transfer in Film Absorption on Horizontal and Vertical Tubes, *Ab-Sorption 96, International Absorption Heat Pump Conference, Montreal, Canada*: p. 409-419

Bredow, D., Jain, P., Wohlfeil, A., Ziegler, F., 2008, Heat and Mass Transfer Characteristics of a Horizontal Tube Absorber in a Semi-Commercial Absorption Chiller, *Int. J. Refrigeration*, Vol. 31, No. 7: p. 1273-1281

Cosenza, F., Vliet, G.C., 1990, Absorption in Falling Water/LiBr Films on Horizontal Tubes, *ASHRAE Transactions*, Vol. 96, No. 1: p. 693–701

Gluesenkamp, K., Radermacher, R., Hwang, Y., 2011, Trends in Absorption Machines, *Proceedings of the International Sorption Heat Pump Conference, Padua, Italy*: p. 13-22

Harikrishnan, L., Maiya, M.P., Tiwari, S., Wohlfeil, A., Ziegler, F., 2009, Heat and Mass Transfer Characteristics of Absorption of R134a into DMAC in a Horizontal Tube Absorber, *Heat Mass Transfer*, Vol. 45, No 12: p. 1483-1491

Harikrishnan, L., Maiya, M.P., Tiwari, S., 2011, Investigations on Heat and Mass Transfer Characteristics of Falling Film Horizontal Tubular Absorber, *Int. J. Heat Mass Trans.*, Vol. 54, No. 11-12: p. 2609-2617

IPCC (2007): *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment .Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, 2007

Islam, M., Wijeysundera, N.E., Ho, J.C., 2003, Evaluation of Heat and Mass Transfer Coefficients for Falling Film Tubular Absorbers, *Int. J. Refrigeration*, Vol. 26, No. 2: p. 197-204

Islam, M.R., 2008, Absorption Process of a Falling Film on a Tubular Absorber: An Experimental and Numerical Study, *Applied Thermal Engineering*, Vol. 28, No. 11-12: p. 1386-1394

Jeong, S., Garimella, S., 2005, Optimal Design of Compact Horizontal Tube LiBr/Water Absorbers, *HVAC&R Research*, Vol. 11, No. 1: p. 27-44

Kang, Y.T., Kim, J.-K., 2006, Comparisons of Mechanical and Chemical Treatments and Nano Technologies for Absorption Applications, *HVAC&R Research,* Vol. 12, No. 3b: p. 807-819

Kang, Y.T., Kim, H.J., Lee, K.I., 2008, Heat and Mass Transfer Enhancement of Binary Nanofluids for H_2O / LiBr Falling Film Absorption Process, *Int. J. Refrigeration*, Vol. 31, No. 5: p. 850-856

Killion, J.D., Garimella, S., 2003, A Review of Experimental Investigations of Absorption of Wator Vapor in Liquid Films Falling Over Horizontal Tubes, *HVAC&R Research*, Vol. 9, No. 2: p. 111-136

Kim, B., Lee, C., 2003, Non-absorbable Gas Effects on Heat and Mass Transfer in Falling Film Absorption, *KSME International Journal*, Vol. 17, No. 4: p. 581-589

Kim, J.-K., Park, C.W., Kang, Y.T., 2003a, Wettability Correlation of Microscale Hatched Tubes for Falling Film Absorption Application, *Journal of Enhanced Heat Transfer*, Vol. 10, No. 4: p. 421-430

Kim, J.-K., Park, C.W., Kang, Y.T., 2003b, The Effect of Micro-Scale Surface Treatment on Heat and Mass Transfer Performance for a Falling Film H_2O/LiBr Absorber, *Int. J. Refrigeration*, Vol. 26, No.5: p. 575-585

Kyung, I.S., Herold, K.E., 2002, Performance of Horizontal Smooth Tube Absorber With and Without 2-Ethyl-Hexanol, *Journal of Heat Transfer*, Vol. 124, No.1: p. 177-183

Kyung, I.S., Herold, K.E., Kang, Y.T., 2007, Experimental Verification of H_2O/LiBr Absorber Bundle Performance with Smooth Horizontal Tubes, *Int. J. Refrigeration*, Vol. 30, No. 4: p. 582-590

Kulankara, S., Herold, K.E., 1999, Theory of Heat/Mass Transfer Additives in Absorption Chillers, *HVAC&R Research*, Vol. 6, No. 4: p. 369-380

Miller, W.A., 1999, The Synergism Between Heat and Mass Transfer Additive and Advanced Surfaces in Aqueous LiBr Horizontal Tube Absorbers, *International Sorption Heat Pump Conference*, Munich, Germany: p. 307-321

Nosoko, T., Miyara, A., Nagata, T., 2002, Characteristics of Falling Film Flow on Completely Wetted Horizontal Tubes and the Associated Gas Absorption, *Int. J. Heat Mass Trans.*, Vol. 45, No. 13: p. 2729-2738

Park, C.W., Kim, S.S., Cho, H.C., Kang, Y.T, 2003, Experimental Correlation of Falling Film Absorption Heat Transfer on Micro-Scale Hatched Tubes, *Int. J. Refrigeration*, Vol. 26, No. 7: p. 758-763

Park, C.W, Cho, H.C., Kang, Y.T., 2004, The Effect of Heat Transfer Additive and Surface Roughness of Micro-Scale Hatched Tubes on Absorption Performance, *Int. J. Refrigeration*, Vol. 27, No. 3: p. 264-270

Pospisil, J., Chroboczek, L., Fortelny, Z., Charvat, P., 2009, Falling Film Heat Exchange and Backsplash on Hoizontal Tube Bundles, *Int. J. Energy*, Vol. 3, No. 3: p. 35-42

Schneider, M.-C., Schneider, R., Zehnacker, O., Buchin, O., Cudok, F., Kühn, A., Meyer, T. Ziegler, F., Seiler, M., 2011, Ionic Liquids: New High-Performance Working Fluids for Absorption Chillers and Heat Pumps, *Proceedings of the International Sorption Heat Pump Conference, Padua, Italy*: p. 95-106

Yoon, J.I., Kim, E., Choi, K.H., Seol, W.S., 2002, Heat Transfer Enhancement With a Surfactant on Horizontal Bundle Tubes of an Absorber, *Int. J. Heat Mass Trans.*, Vol. 45, No. 4: p. 735-741

Yoon, J.-I., Phan, T.T., Moon, C.-G., Lee, H.-S., Jeong, S.-K., 2008, Heat and Mass Transfer Characteristics of a Horizontal Tube Falling Film Absorber with Small Diameter Tubes, *Heat Mass Transfer*, Vol. 44, No.4: p. 437-444

ACKNOWLEDGEMENT

The authors gratefully acknowledge support from the HessenAgentur through Grant Number HA-277/11-22 for this research.

HESSEN

Hessisches Ministerium für
Umwelt, Energie, Landwirtschaft
und Verbraucherschutz